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MILLIMETER WAVE SUPERCONDUCTING DEVICES,(U)
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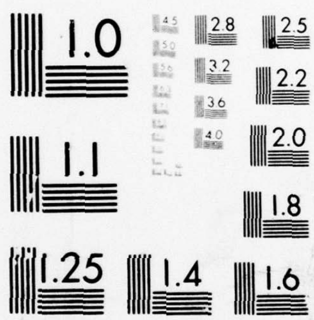

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(6) MILLIMETER WAVE SUPERCONDUCTING DEVICES,

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ABSTRACT

Significant progress has been made during the past two years in the development of millimeter wave superconducting devices. The present status of bolometric detectors and mixers, Josephson effect mixers, quasiparticle mixers, and Josephson effect parametric amplifiers will be reviewed.

INTRODUCTION

The history of high frequency analog superconducting devices has been one of an embarrassment of riches. Many types of devices have been explored which have worked more or less well. In the last few years, however, it has become increasingly clear that the most useful devices will probably be those that perform the conventional functions of detection, mixing and amplification. The author[1,2] and others[3] have published reviews which describe many of the complexities of this subject. The material in these reviews remains generally valid. The purpose of the present article is therefore to report on progress made since 1976.

SUPERCONDUCTING BOLOMETERS

A complete description has been published of the development of superconducting bolometers at Berkeley. Large area (0.16 cm^2) slow (τ = 83 ms) sensitive (NEP + 1.7×10^{-15} $W/\sqrt{Hz}$) bolometers have been made for use as square law (power) detectors at millimeter and submillimeter wavelengths. The thermometer is a superconducting Al film operated at its transition temperature of ~ 1.3K, which is AC biased and read out through a bridge circuit and a step up transformer. The radiation is absorbed in a Bi film on the back side of a sapphire substrate which also supports the thermometer film. The submillimeter absorbtivity has been shown to be 53 ± 5 percent compared with a theoretical value of 50 percent. This bolometer was the first one reported to approach the theoretical noise limit set by thermodynamic energy fluctuations. Recently similar composite bolometer structures with semiconducting thermometers[5] have given comparable results at He^4 temperatures and significantly better results at He^3 temperatures. The status of development of these

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devices is summarized in Table I.

Table I Performance characteristics of 4 × 4mm composite bolometers

Thermometer	Superconducting Al	Ge:Ga	Ge:In:Sb
Bath Temperature (K)	1.27	1.2	.35
Thermal Conductance (W/K)	2×10^{-8}	6×10^{-8}	1.7×10^{-8}
Time Constant (ms)	83	25	6
Electrical NEP ($W/\sqrt{Hz}$)	1.7×10^{-15}	3×10^{-15}	6×10^{-16}

Exploratory experiments have been carried out recently[6] at Berkeley to investigate the use of the superconducting bolometer as an efficient thermal heterodyne mixer. Such a device is able to operate at any RF frequency that can be coupled into it. The IF bandwidth is limited to the thermal relaxation frequency. It should therefore be similar in operation and applications to the InSb hot electron mixer[7] which has found uses in radio astronomy at near millimeter wavelengths despite its limited IF bandwidth of ~ 3MHz. Another possible application is to near-millimeter radar where the bandwidth required is small. The thermal relaxation frequency can be selected over a wide range. A bandwidth of a few MHz can be obtained with a thin film structure immersed in superfluid He[4], or impedance matched to a substrate.[8] In structures such as point contacts and variable thickness bridges, where the excited quasiparticles escape into the surrounding metal, much higher relaxation frequencies and therefore IF bandwidths are expected.[9] Thermal mixing has often been seen in heating dominated Josephson structures.

For a low noise mixer it is necessary to apply a large enough local oscillator power to obtain a power conversion efficiency $\eta = P_{IF}/P_S > 0.1$. The impedance swing from the superconducting to the normal state is in fact large enough to achieve $\eta \approx 1$, if thermal runaway can be avoided. Thermal runaway occurs in a current biased superconductor because the power dissipated by the bias increases with increasing temperature. The best results that have been achieved thus far[6] with Al film mixers in superfluid He is $\eta \approx 0.04$ and $B_{IF} \approx 1MHz$. These values are not yet competitive, but no firm limit has been reached.

JOSEPHSON EFFECT MIXER

The use of a Josephson effect mixer with external local oscillator as a harmonic mixer for frequency comparison[10,11] is the only case in which a Josephson effect high frequency device has ever been used in a practical application for which it was the optimum

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device. Recently there has been considerable hope that point contact Josephson junction mixers operated with an external local oscillator will serve as practical efficient low noise receivers for near-millimeter wavelengths.

Table II shows experimental results for mixer noise temperature obtained by several groups at a variety of frequencies.[12-15]

Table II Mixer noise temperature T_M of several point contact Josephson effect mixers compared with the theoretical prediction of 40 T_{eff}

Frequency (GHz)	Temperature (K)	40 T_{eff} (K)	Experimental T_M (K)
36	1.4	66	54
120	6	266	120
130	4.2	209	180
452	4.2	465	400-1000

The Goddard work[13] at 130 GHz is of particular interest because it employs point contacts which can be recycled repeatedly without a significant change in their characteristics.

In order to understand the optimization of this device quantitatively,[16] an analog junction simulator has been used to compute the detailed experimental parameters of an equivalent circuit which is chosen to represent the actual mixer as closely as possible. The resistively shunted junction model is imbeded in a series resonant RF input circuit with signal and local oscillator source resistance R_S. The DC bias circuit is decoupled at RF frequencies by an inductor. Noise is represented by an equivalent quasiparticle noise current source which has the form $I_n^2 = 2kTB/R$ in the thermal limit when $2kT > h\nu$ and $I_n^2 = h\nu B/R$ in the photon limit when $h\nu > 2kT$. Here B is the bandwidth and R the junction shunt resistance. Quasiparticle shot noise is not important in this device since $h\nu > eV$. There is some uncertainty about the need for an additional pair shot noise term in this simulation. The point contact junction is not well enough characterized to answer the question theoretically and the experimental evidence appears to be contradictory.[12,17]

In the simulation, the output is represented by an equivalent circuit consisting of an IF current generator in series with the dynamic resistance of the junction. One important result of the simulations is a value for the equivalent output noise current $I_{no}^2 = \beta^2 I_n^2$ in the thermal limit and $\gamma^2 I_n^2$ in the photon limit. If the input coupling is weak ($R_S \gtrsim 4R$) then β^2 and γ^2 are nearly

identical functions of the normalized frequency $\Omega = h\nu/2eI_cR$ over the range $0.1<\Omega<1$. Experimental measurements of $\beta^2(\Omega)$ for weakly coupled junctions at 36[12] and 130 GHz[4] lie within a factor 2 above the calculation for $0.1<\Omega<1$. The similarity of $\beta^2(\Omega)$ and $\gamma^2(\Omega)$ shows that the noise in the photon limit can be represented by replacing the ambient temperature T by an effective temperature $h\nu/2k$ when $h\nu>2k$.

For efficient mixer operation it is necessary to couple the junction relatively tightly to the input RF circuit, so that $1<(R_S/R)<4$. In this case the mixer performance becomes a complicated function of nearly all of the mixer parameters. The simulator was used to explore the parameter spare to predict conversion efficiency and mixer noise temperature for the assumed equivalent circuit. Conversion efficiencies $\gtrsim 0.3$ are available for $0.1<\Omega<1$. The best value of single-sideband mixer noise temperature computed was $T_M \approx 40T_{eff}$ $(0.1<\Omega<1)$ where T_{eff} is the larger of the ambient temperature or $h\nu/2k$. The theoretical predictions are compared with experiments in Table II. Although these experimental results represent the lowest mixer noise temperatures reported in this frequency range, the margin of improvement over cooled conventional Schottky diode mixers is not very wide. It is of importance for the future Josephson mixers to obtain better results. The simulations do not preclude the possibility of $T_M < 40T$, if a more favorable mixer circuit is discovered. It may be that this has occurred in the work at 120 GHz.[13]

QUASIPARTICLE MIXERS

The I-V curve for quasiparticle tunneling in superconductor-insulator-superconductor (SIS), superconductor-insulator-normal metal (SIN), and superconductor-insulator-semiconductor (super-Schottky) junctions has sharp enough curvature that their use in classical mixers and detectors is very promising. The super-Schottky is the most extensively explored device of this type. The mixer noise temperature of $T_M = 6K$ and Video NEP $= 5 \times 10^{-16}$ W/$\sqrt{Hz}$ observed at X-band by the Aerospace group[18] are an order of magnitude better than has been observed with any other diode. As with the conventional Schottky diode, the limit to the operating frequency is set by the discharge of the junction capacitance through the series (spreading) resistance in the semiconductor. The cut-off frequency has been quite low in the super-Schottky diodes used thus far. Super-Schottky diodes with very thin single crystal Si as the semiconductor layer are now being fabricated[19,20] which are expected to extend the operating range of these very promising devices to higher frequencies.

Preliminary experiments have begun at Berkeley and Boulder[21] to explore the properties of classical mixing in SIS and SIN tunnel junctions. The SIS case has larger curvature in the I-V curve, but is complicated by the Josephson effect. It is not promising to use an SIS tunnel junction as a Josephson mixer with an external local oscillator because junctions with sufficient current density to eliminate the hysteresis on the I-V curve are not yet available, and the hysteretic Josephson mixer is rather noisy.[22] Only a moderate critical current density is required, however, to make a classical mixer at millimeter wavelengths. It appears to be sufficient to make the capacitative reactance of the shunt capacitance at the operating frequency large compared with the normal resistance of the junction. This occurs at 36 GHz in Pb-Pb junctions with a current density of $\sim 300 A/cm^2$. Another requirement is that the junction resistance be large enough to match easily to the RF and microwave circuits. Junction resistances in the neighborhood of 100Ω are available with junction dimensions of a few μm.

When an increasing local oscillator power is applied to an SIS junction, Josephson steps move out to larger voltages. When the Josephson steps appear near the knee in the quasiparticle tunneling curve, which is the DC bias point chosen for this mixer, then strong Josephson mixing effects are seen. This occurs when the swing in the local oscillator voltage is wide enough to include zero voltage. For smaller amounts of local oscillator power, the I-V curve in the neighborhood of the bias point is dominated by photon assisted tunneling effects and essentially classical mixing phenomena are seen. Although the mixer noise in this mode appears to be quite low,[21] detailed measurements have not yet been made.

EXTERNALLY PUMPED PARAMETRIC AMPLIFIER

Josephson effect parametric amplifiers with both internal[23,24] and external pump have been explored. There has been more progress with the externally pumped devices recently so this discussion will focus on them.

We first consider the four photon doubly degenerate parametric amplifier or SUPARAMP invented by Chiao which has $\omega_S + \omega_I = 2\omega_P$. Detailed theoretical investigations of this device have been carried out by Chiao and his coworkers at Berkeley[25,26] based on the assumption that the Josephson element is RF voltage biased. All of the early experimental work, however, was carried out with series arrays of Dayem bridges[25] or point contacts[27] which were RF current biased. Efforts have been made to produce an adequate theory of the current biased device.[27] Significant gain has been observed at frequencies as high as 36 GHz,[28] but the gain is accompanied by amplified junction noise which appears to be related to phase instabilities

that occur when the RF current exceeds I_c.[29]

A new experimental approach has been made by the Gothenberg group[30] who have operated a SUPARAMP constructed from a series array of tunnel junctions. This device is used in a mode in which each junction is RF voltage biased by the parallel junction capacitance. A magnetic field in the plane of the junctions is used to adjust the amplifier to an operating point with large (non-reentrant) gain. Very good agreement is found between the performance of this amplifier and the theory of the voltage biased SUPARAMP.[25]

An entirely separate line of development of externally pumped Josephson parametric amplifiers has been pursued by the group at the Technical University of Denmark. This work started with the discovery made using a junction simulator that when a tunnel junction is pumped at twice the Josephson plasma resonance frequency ω_J, then a parametric oscillation is excited at ω_J. The properties of a three photon singly degenerate parametric amplifier with $\omega_P = \omega_S + \omega_I$ were then calculated.[31] Significant gain has recently been observed at X-band using a single Josephson tunnel junction.[32]

The use of tunnel junctions in Josephson high frequency devices can be considered to be a favorable development because they are well characterized and have minimal heating effects. It can be anticipated that the heavy investment in Josephson effect computers will make stable reproducible tunnel junctions available with a wide variety of junction parameters.

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